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Economic Analysis

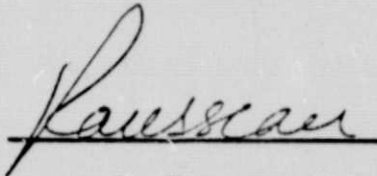# DEVELOPMENT OF A SOLAR-POWERED RESIDENTIAL AIR CONDITIONER

Contract NAS8-30758

74-10906(4)

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INTRODUCTION

This report summarizes the results of investigations aimed at the development of cost models to be used in the economic assessment of Rankine-powered air conditioning systems for residential application. These investigations were conducted in fulfillment of Task 3, Economic Analysis, of Contract NAS8-30758.

The rationale used in the development of the cost model was to: (1) collect cost data on complete systems and on the major equipment used in these systems; (2) reduce these data and establish relationships between cost and other engineering parameters such as weight, size, power level, etc; and (3) derive simple correlations from which system cost-to-the-user can be calculated from performance requirements.

These cost models will be used for the purpose of system evaluation and tradeoff studies. The final cost of the selected system will be determined more accurately through detailed cost estimates using equipment sizes and problem statements derived from the system and component analyses.

The equipment considered in this survey includes heat exchangers of various types, fans, motors, and turbocompressors. This kind of hardware represents more than 2/3 of the total cost of conventional air conditioners.

A description of the system cost model follows. Further discussions are concerned with the assumptions and rationale used in the development of the model. The data are arranged as they pertain to the overall system or components.

SUMMARY

A method has been developed from published cost data whereby total system cost can be determined from the cost of the major components. The following relationships were derived:

Manufacturer's price = 2.37 (Σ component OEM cost)

User's cost = 2.86 (manufacturer's price)

The manufacturer's price includes allowances for structures and cabinets, system assembly, direct and indirect labor, administrative and operating expenses, profit, etc. The user's cost includes services provided by the distributor/dealer and includes installation cost.

The components considered in computing system cost include heat exchangers, fans and motors, pump and motor, wiring and controls, and turbocompressor. Models were developed for estimating the cost of these components on an original equipment manufacturer (OEM) basis. Equipment costs furnished by various equipment manufacturers were analyzed and correlated to engineering parameters such as heat exchanger weight. Table I summarizes component cost relationships.

TABLE 1

COMPONENT COST MODELS
(DOLLARS)

Component	International Units	English Units
Heat exchangers		
Evaporator and condenser*	4.0 (core weight, kg)	1.8 (core weight, lb)
Boiler*	7.9 (heat exchanger weight, kg)	3.6 (core weight, lb)
Fans (excluding motors)**	4.8 (fan weight, kg)	2.2 (fan weight, lb)
Motors[†]	25 + 32.5 kw	25 + 32.5 kw
Pump (with motor)	50	50
Turbocompressor	100	100
Wiring and controls	10 percent of system cost	10 percent of system cost

*Weight calculated from heat transfer requirements.

**Fan weight estimated from Figure 5.

[†]Motor output kw estimated from fan power of Figure 5.

MAJOR ASSUMPTIONS

The air conditioning industry is highly competitive, and price information is very sensitive. Air conditioners are marketed from the factory through a system of distributorships and dealerships to the consumer. List prices established by the manufacturer represent the price that the user will ultimately pay for the equipment. List prices, however, are used mostly as a base from which the actual prices to the distributor, dealer, and consumer are computed.

Because of the sensitivity of the cost information and the various data sources used in the development of the models, it has been necessary to make certain assumptions relative to the cost buildup from the manufacturer to the user. Figure 1 shows the model used to derive user's cost from the manufacturer sell price.

Normally, the manufacturer price to the distributor is about 35 percent of the list price. The distributor markup is roughly 100 percent to cover transportation, storage, servicing, training, profit, and other expenses.

Discounts to the contractor amounting to 30 percent of list price appear to be normal. However, depending on the size of the order and the business arrangements between the contractor and the distributor, larger discounts can be negotiated. For the purpose of these investigations, the cost to the contractor was taken as 70 percent of list price (corresponding to a 43 percent markup).

The contractor will procure the equipment from the distributor, and realize a profit on the equipment; in addition, installation charges will be passed on to the user. As a rule, the total contractor contribution to cost-to-user will be about 30 percent of the list price. Consequently, the cost to the user will be about the same as the list price.

On the basis of these assumptions, the installed cost of a system can be computed from the factory sell price using the correlation

$$\text{Installed cost} = 2.86 \text{ (factory sell price)}$$

This value agrees fairly well with data derived by the General Electric Company* as representative of mass-produced air conditioning equipment.
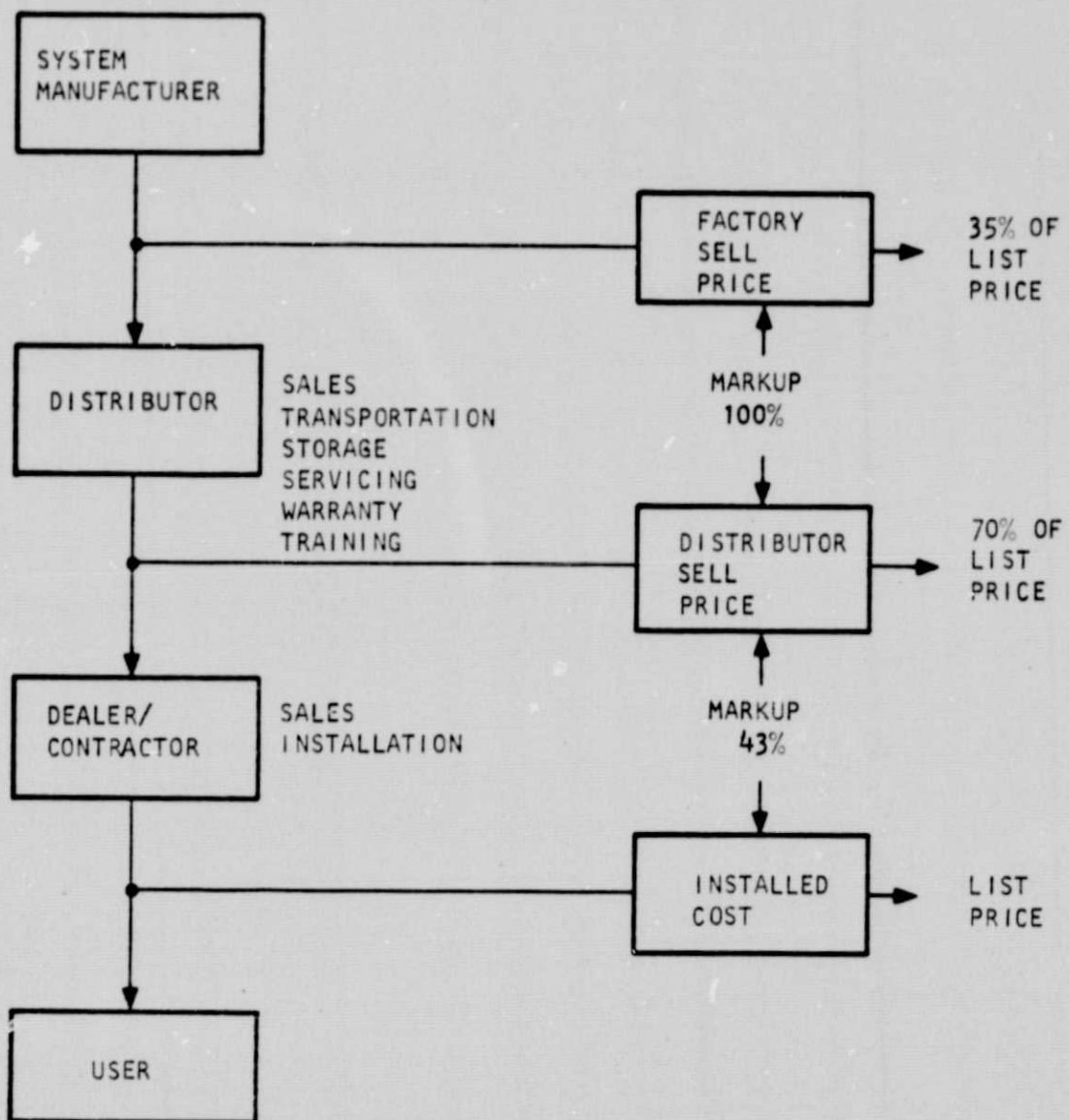
SYSTEM COST DATA

Figure 2 is a simple schematic of a Rankine-powered air conditioner. The major components constituting the complete system are:

(a) Heat exchange --boiler, evaporator, and condenser

(b) Motor-driven fans--evaporator and condenser

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*"Solar Heating and Cooling of Buildings, Phase 0 Final Report," NSF RA-N-74-021A, Volume 1, Executive Summary, General Electric Company, May 1974.

INSTALLED COST = 2.86 X (FACTORY SELL PRICE)

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Figure 1. Manufacturer-to-User Cost Buildup
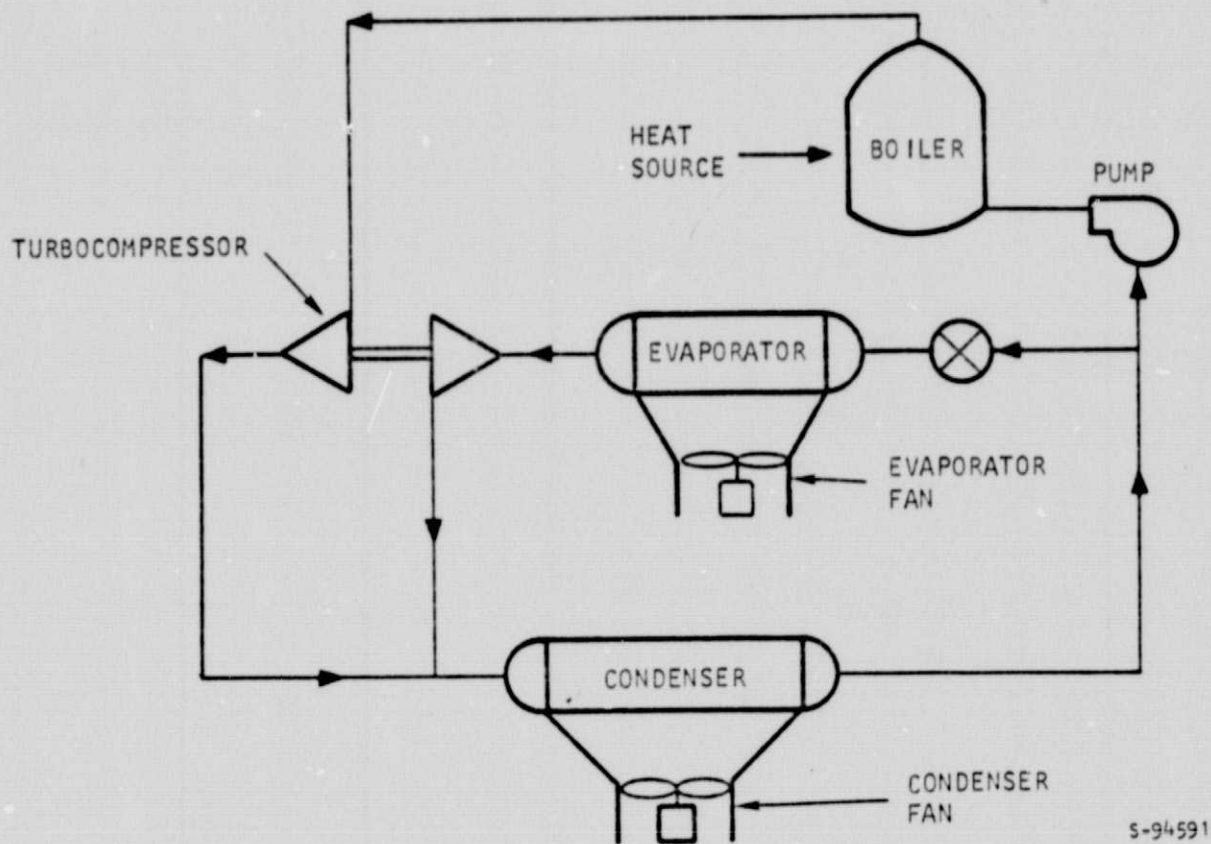
Figure 2.   Rankine-Powered Air Conditioner

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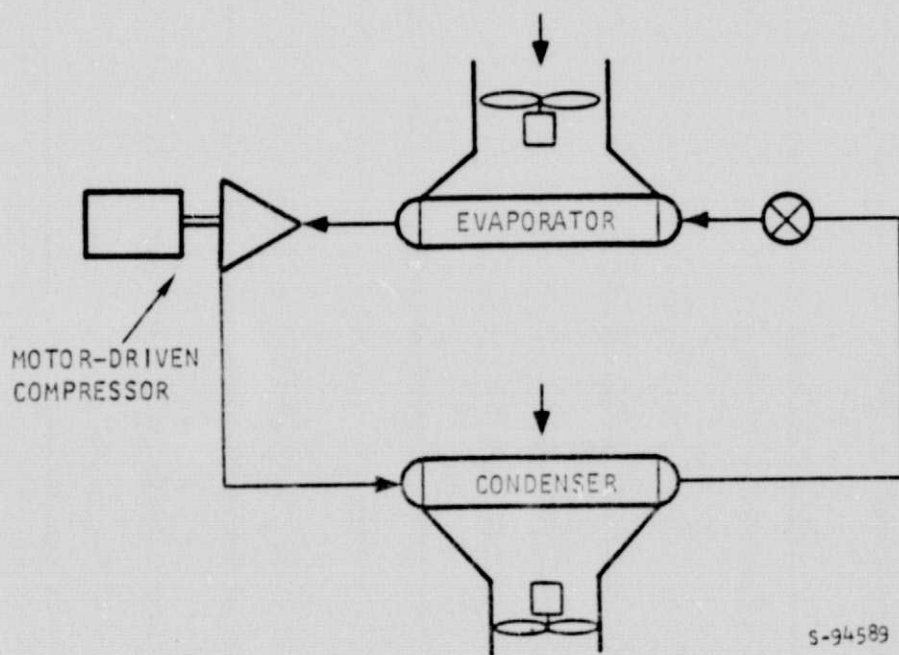
Figure 3.   Conventional Electric-Driven Air Conditioner

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(c) Turbocompressor

(d) Motor-driven pump

Not illustrated are the controls, wiring harnesses, structures, and enclosures.

The schematic also does not include any means of augmenting the solar heat source. The additional equipment necessary for this purpose will be considered later, and cost models for this hardware will be generated when the approach for system augmentation is selected and the final system schematic is developed.

Fundamental schematic and hardware differences exist between conventional electric-driven and Rankine-powered air conditioners (see Figures 2 and 3). However, much of the hardware used in both systems is the same type--condenser, evaporator, fans, controls, and overall package. These similarities allow cost data on conventional systems to be used as a basis for estimating Rankine system cost. A breakdown of the percentage of factory direct cost for the various components of residential air conditioners is listed below. These data were obtained from a large manufacturer of this type of equipment.

Heat exchangers (evaporator, condenser)	14 percent
Motor-driven fans (evaporator, condenser)	21 percent
Motor-driven compressor	25 percent
Wiring and controls	10 percent
Structure and enclosures	19 percent
System assembly	11 percent
Total direct cost	100 percent

The factory direct cost is defined as the actual expenditures directly related to the fabrication of a system, including the cost of materials, shop labor, and shop setup for a production run; it does not include shop overhead, administrative expenses, or profit.

The class of equipment for which the cost breakdown is listed above is represented by air conditioners in the capacity range from 1-1/2 to 5 tons. These air conditioners are designed primarily for the residential market. Since minimum cost is a design goal, these units feature relatively low heat exchanger effectivenesses with approach temperatures between 269.3 and 272 K (25 and 30°F). COP's at standard ARI conditions* between 1.6 and 2.0 are representative of this class of equipment.

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*Ambient air temperatures: 308.2 K (95°F) db and 297 K (95°F) wb
Return air temperatures: 299.8 K (80°F) db and 292.6 K (67°F) wb

Small capacity air conditioners of higher quality also are available with COP's as high as 4.0. The higher performance of these units is achieved through the use of larger heat exchangers and a higher capacity condenser fan; the compressor and controls are the same as for the lower cost units. The equipment cost breakdown for these units is slightly different from that of the lower performance units, with a larger portion of the total cost contributed by the heat exchangers and fans. However, the fraction of the cost attributable to the structure and enclosures is roughly the same as that listed above (19 percent). The portion of the cost reflecting assembly labor (11 percent) also will remain about the same.

As will be discussed later, the cost of heat exchangers and fans is directly related to their weight and size. Since the major portion of a system in terms of bulk and weight involves the heat exchangers and fans, it is reasonable to assume that the 19 and 11 percent contribution of structure/enclosures and assembly also will apply to Rankine air conditioners. It is important to note here that the heat exchangers of solar-powered air conditioners will be designed for higher effectiveness than conventional systems. However, the relationship should hold since the weight, size, and cost of the heat exchanger-fan subassemblies are the determining factor in establishing system level weight and costs, even for conventional systems. It follows that system factory direct cost can be determined from the OEM cost of the components using the relationship

$$\text{System factory direct cost} = \frac{1}{0.7} \; (\Sigma \text{ component OEM costs})$$

The factory sell price can be determined from the factory direct cost by including overhead and markup. The following factors were considered in establishing factory sell price:

(a) Labor constitutes about 11 percent of the total system cost for systems in the 7.0- to 10.5-kw (2- to 3-ton) capacity range

(b) Shop overhead is estimated at 2.5 times the direct labor cost so that shop overhead can be approximated by

   Shop overhead = 0.275 (factory direct cost)

(c) A 30 percent markup was used to cover administrative expenses, engineering, accounting, profit margin, etc. Using these factors, the factory sell price of a system can be calculated from

   Factory sell price = 2.37 (Σ component OEM costs)

The cost of a number of conventional electric-driven air conditioners was compiled from manufacturers' catalogues. The actual factory sell price of such equipment was approximated using the relationships discussed previously (see Figure 1). These cost data were correlated using weight as the reduction factor. It was found that of the 36 air conditioners considered, the list prices varied between $4.50/kg to $5.50/kg ($2.00/lb to $2.50/lb) corresponding to factory sell prices lower than $2.50/kg ($1.00/lb). As discussed previously, this relationship holds for a given class of residential equipment.

Dat: for larger capacity units may differ considerably. Higher effectiveness units will be somewhat more expensive since the high cost components (heat exchangers and fans) will be larger, thus driving the cost of the entire package up.

COMPONENT COST DATA

Previous discussions have shown that system costs can be estimated if the cost of the major system components are known. The cost of components will be determined primarily by the cost of the materials used in fabrication and by the labor cost as affected by the design sophistication of the equipment.

The following discussions are concerned with the cost models that were developed to characterize heat exchangers, pumps, turbomachinery, fans, and motors.

Heat Exchangers

Two types of heat exchangers will be used in Rankine-powered air conditioners: finned tube units for the evaporator, and the condenser and shell and tube units for the boiler.

The finned tube units consist of copper tubing staggered in the direction of the air flow with wavy aluminum fins mechanically bonded to the tubes on the airside. These fins enhance the airside conductance of the unit so that heat transfer conductances on both sides are approximately equal for a condenser or evaporator operating under typical conditions.

Detailed data provided by heat exchanger manufacturers indicate that the quantities of copper (for the tubes) and aluminum (for the fins) used in the fabrication of a typical core are approximately the same. The quantity of steel used for the frame will vary considerably, depending on the size of the unit and on the particular package design. A rough approximation for low capacity heat exchangers is that the weight of the frame will represent about 10 percent of the total unit. Current prices for these materials are:

Copper tubing	$2.93/kg ($1.33/lb)
Aluminum sheet	$1.28/kg ($0.58/lb)
Simple steel sections	$0.48/kg ($0.22/lb)

Combining the prices with the weight relationships above yields an average specific cost of $1.95/kg ($0.89/lb).

The factory total cost of such a unit includes the following elements:

    Material cost
    Labor cost
    Setup cost
    Shop overhead

Relationships have been established that show that the last three cost categories represent 30 percent of the total cost of a typical unit. Thus the following relationship can be written:

$$\text{Factory total cost} = \frac{\text{Material cost}}{0.7}$$

Manufacturer markup, including administrative and operating expenses other than factory, is about 30 percent; so the factory sell price can be computed from the core weight (or core volume) of a heat exchanger by

Heat exchanger factory sell price, dollars = 4.0 (HX core weight, kg) or 1.8 x (HX core weight, lb)

In turn, the core weight can be determined from the performance requirements for the unit.

The shell and tube units that will be used as boilers consist of copper tubes incorporating extended surfaces within the tube to maximize the heat transfer conductance within the tube where the working fluid is evaporated. The entire unit is fabricated of copper and brass. The cost of the units is estimated in a fashion similar to that of the finned tube units. Original equipment manufacturer's price for the finned tube is $1.64/m ($0.50/ft).

The factory cost for this type of heat exchanger is estimated at $6.05/kg ($2.75/lb) of heat exchanger. Factory sell price is about $7.90/kg ($3.60/lb) for an all-copper alloy unit.

The weight of the unit can be determined from the heat transfer area necessary to satisfy thermal requirements.

Refrigerant Pumps

Preliminary estimates of the refrigerant pump requirements indicate that in the specific speed range of interest, a centrifugal pump would have a peak efficiency lower than 20 percent. By comparison, a small vane pump in the size of interest (3500 rpm, N_s < 300, 2 to 4 gpm) is available commercially. The original equipment manufacturer price on this type of pump is about $20 for the pump element itself. With a canned motor to eliminate leakage, the entire assembly cost is estimated at about $40. Slightly lower prices could be obtained with very large production quantities (in excess of 100,000 units per year).

Turbocompressors

Cost data on turbocompressors of considerable aerodynamic sophistication were obtained from the AiResearch Industrial Division (AID) of The Garrett Corporation. The current AID turbocompressor yearly production level is 350,000 units. About half of these are a single model, with the remainder representing various models. Figure 4 is a plot of turbocompressor cost as a function of production rate. The plot was obtained by combining current AID production data with estimated data for very large quantities.
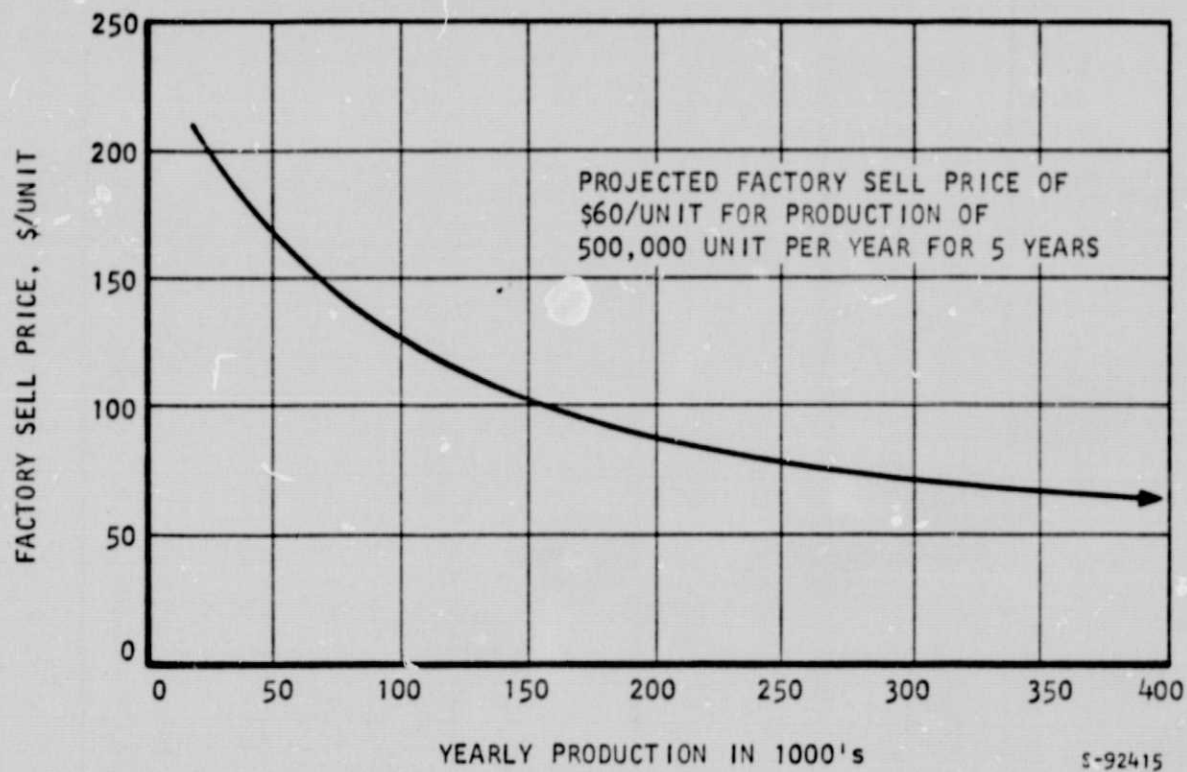
Figure 4. Turbocompressor Cost Data

In the case of the turbocharger, material cost is a small portion of the total cost of the unit. This may not be true of very large production orders. One important design consideration is the low temperature level of the turbine and compressor. Possibly the use of plastic as construction material could offer the potential for significant cost reductions. Detailed cost estimates for the turbomachinery will be developed later in Task 5 of the program. For the purpose of system comparison, a unit price of $100 per unit will be used.

Fans and Blowers

The type of fan or blower selected for a particular application depends primarily on pressure rise and flow requirements and cost. Generally, squirrel cage blowers are used. This type of blower can be designed to cover a wide range of flow rates, up to $12 m^3$/sec (25,000 cfm) over a range of pressure rise from 0 to 1.24 kN/m^2 (5 in. H_2O). Squirrel cage blowers are relatively inefficient in the size normally used in residential systems. Low capacity blowers less than $0.71 m^3$/sec (1500 cfm) are marketed with efficiencies between 20 and 40 percent. Larger capacity units used primarily in commercial and industrial applications have efficiencies as high as 65 percent.

For high flow rates and low pressure rise (less than 124 N/m^2 (0.5 in. H_2O), tube axial fans can be used. The peak efficiency of these fans is generally lower than that of the squirrel cage blowers. This type of fan is rather wasteful of energy and will not be considered further.

For high flow rates where fan efficiency is more important, vane axial fans are often preferred. This type of fan can be designed to cover the range of flows and pressure rise attainable with squirrel cage blowers. The efficiency of these fans is significantly higher--as high as 70 percent. Cost also is higher by a factor of about 1.5.

For the application under consideration, it is important to minimize parasitic power usage (fan and pump motors), which could easily amount to 1 kw of continuous power for a 3-ton unit. To accomplish this, an investigation was conducted to characterize fans in terms of weight, size, rpm, and power requirement. The type of fan selected is a vane-axial fan for the entire range of flow rates (0 to 2.35 m^2/sec (5000 cfm)) and pressure rise (124 to 1240 N/m^2 (0.5 to 5 in. H_2O)) considered. The fan characteristics are shown in Figure 5. The data shown are based on fan efficiencies of 70 percent over the entire range of flow and pressure rise considered. The weight data of Figure 5 are for units of steel construction and do not include the weight of the motor necessary to drive the fan.

Manufacturers' catalogues and price lists were used to determine fan cost. The OEM cost of fans (steel units) can be approximated at $3.30/kg ($1.50/lb) for squirrel cage and $4.80/kg ($2.20/lb) for vane axial fans. The latter value will be used in estimating fan cost from the weight data.

Electric Motors

Electric motors for driving fans and blowers of residential air conditioners will be designed for operation from a single-phase 60 Hz, 115/230 v source.
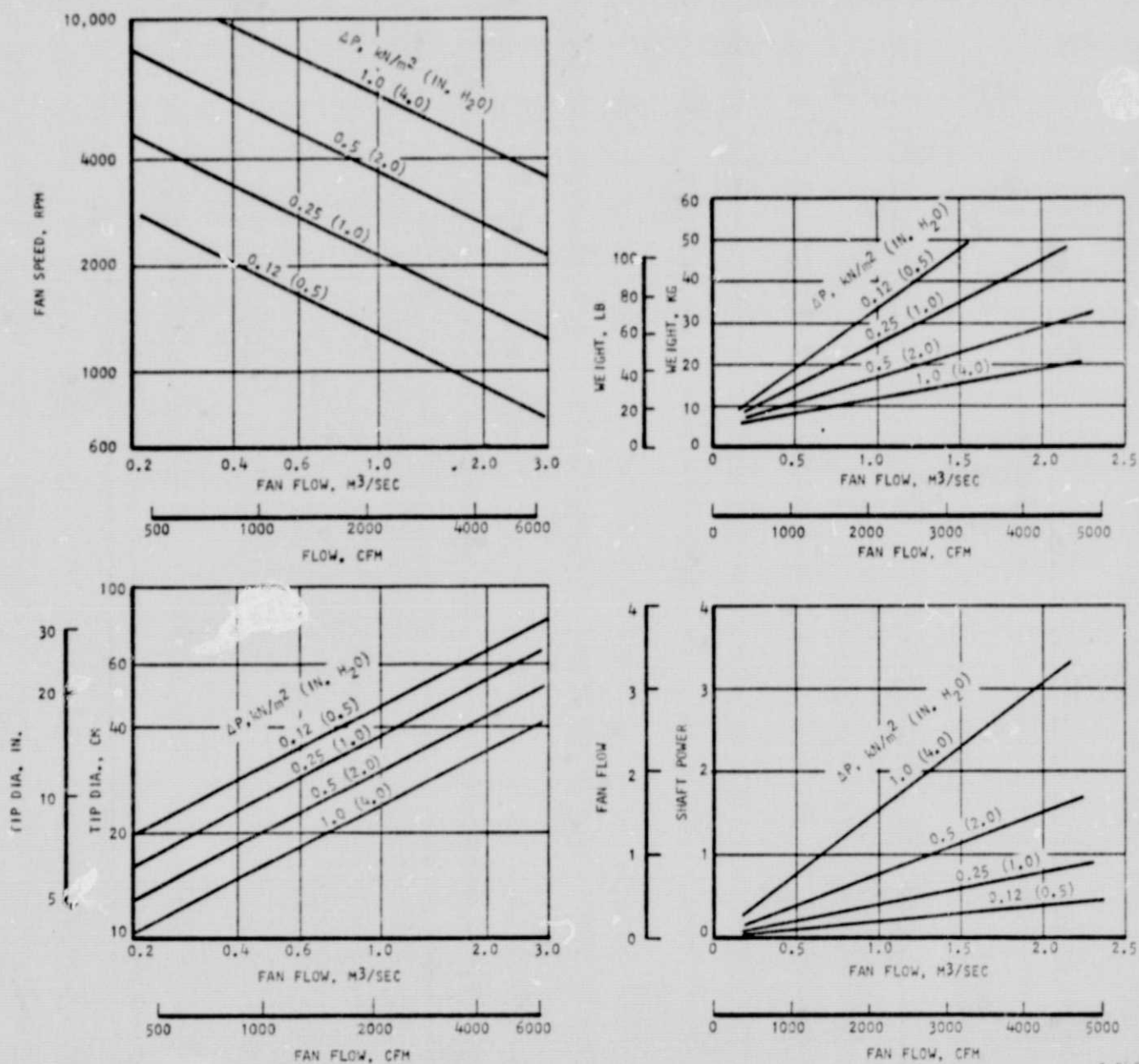
Figure 5. Fan Characteristics

Common speeds for these motors will depend on the number of poles as follows:

2 poles	3450 rpm
4 poles	1725 rpm
6 poles	1140 rpm
8 poles	850 rpm

Detail matching of the system fan and motor is beyond the scope of the current work. Generally, the fan speed characteristics should be selected to match the torque-speed input of a given motor in order to reduce cost. The type of motor selected for a particular application will depend on the starting torque characteristics desired and the efficiency of the motor. The selection of a motor involves tradeoffs between direct and belt drive approaches to assure optimum efficiency and minimum cost.

Figure 6 is a plot of original equipment manufacturer (OEM) prices of small electric motors, up to 1.1 kw (1.5 hp) output. Data are given for various speed motors, and for units designed for shaft-mounted or belt-driven fans and blowers.

The cost of a direct-drive motor is higher than that of a unit designed for a belted fan; however, the cost of the drive set should be added to that of the motor in determining overall cost. In the power range of interest, the OEM price of belt drives is estimated at about $15. Examination of Figure 6 shows that total cost of the motor and belt drive system could be higher than that of a direct drive motor.

The efficiency of commercial motors of the size and type considered here (permanent split capacitor motors) will range from 50 to 60 percent. Efficiency improvements are possible and highly desirable in order to reduce the auxiliary power required for operation of a Rankine-driven air conditioner. However, such improvements will result in higher cost. Detailed evaluation of this factor will be conducted as part of the system optimization tasks.

For the purpose of system selection and parametric analysis, belt-drive motors will be assumed to permit fan operation at the optimum speed. High efficiency fans of small capacity require high rotational speed. The 1725-rpm motor curve of Figure 6 will be used; a $15 allowance will be made for the belt drive.

System Controls

Cost of controls and wiring harnesses represents only a small portion of the total system cost, as noted previously. In a Rankine-powered air conditioner, the control system will be somewhat more complex than that of a conventional unit. Here, controls will be necessary to (a) activate the liquid pump and fans, (b) provide overspeed protection for the turbomachinery, (c) control the speed of the turbocompressor according to a preset schedule to prevent
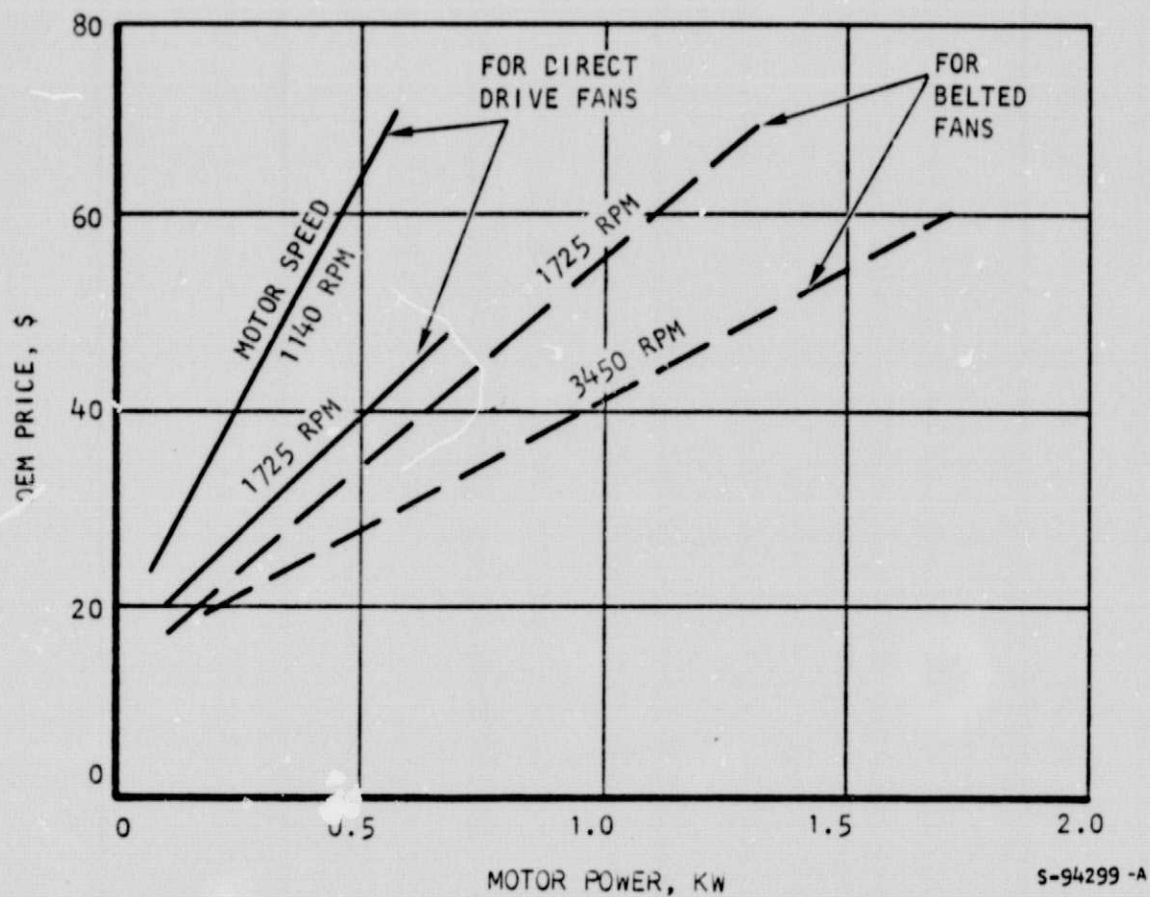
Figure 6. Cost of Single Phase, 60 Hz, 115/230v
Electric Motors

compressor surge, and (d) switch on (and off) the auxiliary equipment to supplement the system when solar thermal energy is not sufficient to drive the system.

At this time, controls constitute a gray area that will not be defined until the entire system concept is developed and optimized. For a first approximation, the cost of controls and wiring harnesses will be taken as 10 percent of the total system cost. This value may be somewhat conservative for large systems, but is adequate for modeling systems in the capacity range of 7.0 to 10.5 kw (2 to 3 tons).